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Review

E-waste: An assessment of global production and environmental impacts

Brett H. Robinson *

Department of Soil and Physical Sciences, Lincoln University, Lincoln 7647, Canterbury, New Zealand

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ABSTRACT

E-waste comprises discarded electronic appliances, of which computers and mobile telephones are disproportionately abundant because of their short lifespan. The current global production of E-waste is estimated to be 20–25 million tonnes per year, with most E-waste being produced in Europe, the United States and Australasia. China, Eastern Europe and Latin America will become major E-waste producers in the next ten years. Miniaturisation and the development of more efficient cloud computing networks, where computing services are delivered over the internet from remote locations, may offset the increase in E-waste production from global economic growth and the development of pervasive new technologies. E-waste contains valuable metals (Cu, platinum group) as well as potential environmental contaminants, especially Pb, Sb, Hg, Cd, Ni, polybrominated diphenyl ethers (PBDEs), and polychlorinated biphenyls (PCBs). Burning E-waste may generate dioxins, furans, polycyclic aromatic hydrocarbons (PAHs), polyhalogenated aromatic hydrocarbons (PHAHs), and hydrogen chloride. The chemical composition of E-waste changes with the development of new technologies and pressure from environmental organisations on electronics companies to find alternatives to environmentally damaging materials. Most E-waste is disposed in landfills. Effective reprocessing technology, which recovers the valuable materials with minimal environmental impact, is expensive. Consequently, although illegal under the Basel Convention, rich countries export an unknown quantity of E-waste to poor countries, where recycling techniques include burning and dissolution in strong acids with few measures to protect human health and the environment. Such reprocessing initially results in extreme localised contamination followed by migration of the contaminants into receiving waters and food chains. E-waste workers suffer negative health effects through skin contact and inhalation, while the wider community are exposed to the contaminants through smoke, dust, drinking water and food. There is evidence that E-waste associated contaminants may be present in some agricultural or manufactured products for export.

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* Tel.: +64 3 3218471.
E-mail address: brett.robinson@lincoln.ac.nz.

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1. Introduction

E-waste and Waste Electrical and Electronic Equipment (WEEE) describe discarded appliances that use electricity. E-waste describes waste electronic goods, such as computers, televisions and cell phones, while WEEE also includes traditionally non-electronic goods such as refrigerators and ovens. Table 1 lists some common WEEE items.

The distinction between E-waste and WEEE is becoming less sharp due to the advent of pervasive computing (Kohler and Erdmann, 2004), where programmable microprocessors are incorporated into electrical equipment, such as refrigerators, which are not normally considered electronic items (Hilty, 2005). However, it is the rapid growth of computing that is driving E-waste production. In the next five years, one billion computers will be retired (Ladou and Lovegrove, 2008).

E-Waste is chemically and physically distinct from other forms of municipal or industrial waste; it contains both valuable and hazardous materials that require special handling and recycling methods to avoid environmental contamination and detrimental effects on human health. Recycling can recover reusable components and base materials, especially Cu and precious metals. However, due to lack of facilities, high labour costs, and tough environmental regulations, rich countries tend not to recycle E-waste. Instead, it is either landfilled, or exported from rich countries to poor countries, where it may be recycled using primitive techniques and little regard for worker safety of environmental protection (Cobbing, 2008). Although illegal under the Basel Convention of 1992 (UNEP, 2009), E-waste exportation continues through clandestine operations, legal loopholes, and by countries that have not ratified the convention.

Table 1
List of common Waste Electrical and Electronic Equipment (WEEE) items, including those normally considered as E-waste.

Item	Wt of Item (kg)	Typical life (year)
WEEE normally considered E-waste		
Computer[a]	25	3
Facsimile machine	3	5
High-fidelity system[b]	10	10
Mobile telephone[b]	0.1	2
Electronic games[b]	3	5
Photocopier	60	8
Radio[b]	2	10
Television[c]	30	5
Video recorder and DVD player[b]	5	5
WEEE not normally considered E-waste		
Air conditioning unit	55	12
Dish washer[b]	50	10
Electric cooker[b]	60	10
Electric heaters[b]	5	20
Food mixer[b]	1	5
Freezer[b]	35	10
Hair dryer[b]	1	10
Iron[b]	1	10
Kettle[b]	1	3
Microwave[b]	15	7
Refrigerator[b]	35	10
Telephone[b]	1	5
Toaster[b]	1	5
Tumble dryer[b]	35	10
Vacuum cleaner[b]	10	10
Washing machine[b]	65	8

[a] (Betts, 2008a).
[b] (Cobbing, 2008).
[c] (Li et al., 2009).

The environmental effects of E-waste disposal are drawing increasing attention from politicians, Non Governmental Organisations (NGOs) such as Greenpeace (www.greenpeace.org), the Basel Action Network (www.ban.org), the Silicon Valley Toxics Coalition (www.svtc.org), as well as the scientific community. As of June 2006, there were more than 500 scientific articles dealing with E-waste and its environmental effects.

This review aims to assess the global production of E-waste, the contaminants and contaminant fluxes associated with E-waste, and the likely environmental impact of E-waste associated contaminants. This paper focuses on the physical, chemical and environmental effects of E-waste, rather than E-waste associated politics, which are discussed extensively in publications from the aforementioned NGOs.

2. The current and future global production of E-waste

In 2006, the world's production of E-waste was estimated at 20–50 million tonnes per year (UNEP, 2006), representing 1–3% of the global municipal waste production of 1636 million tonnes per year (OECD, 2008). Cobbing (2008) calculated that computers, mobile telephones and television sets would contribute 5.5 million tonnes to the E-waste stream in 2010, rising to 9.8 million tonnes in 2015. In rich countries, E-waste may constitute some 8% by volume of municipal waste (Widmer et al., 2005).

The contribution of an item to the annual E-waste production, E (kg/year) depends on the mass of the item, M (kg), the number of units in service, N, and its average lifespan, L (years) [1].

$$E = \frac{MN}{L} \tag{1}$$

Computers, which have an average lifespan of three years (Betts, 2008a), comprise a greater proportion of WEEE than refrigerators and ovens, which have lifespans of 10–12 years. Table 1 provides a list of some WEEE items along with their mass and expected lifetimes.

2.1. An estimation of global E-waste production

Calculating global E-waste production requires information on the number of items in service. These data are generally available in rich countries so E-waste production can be calculated using Eq. (1). Switzerland produces 9 kg per person per year (Sinha-Khetriwal et al., 2005). Europeans produce E-waste at a rate of 14 kg per person per year (Goosey, 2004), making a total annual E-waste production for the 15-member-state European Union (EU-15) of 5.5 million tonnes per year, and the EU-27 of 8.3–9.1 million tonnes per year (Huisman and Magalini, 2007). The United States produced some 2.63 million tonnes in 2005 (Cobbing, 2008), while China produced 2.5 million tonnes (Liu et al., 2006). E-waste production data for poorer countries are less readily available. India and Thailand are estimated to have, respectively, produced just 0.33 and 0.1 million tonnes of E-waste in 2007 (Cobbing, 2008).

Summing the available data indicates that the global production of E-waste was at least 13.9 million tonnes per year in the middle of this decade. This figure does not include Latin America, Africa, Canada or Russia and does not account for the growth in the last four years.

An independent estimation was obtained using Eq. (1) using data from Table 1 and data for the total number of computers (0.78 bn [2004]), mobile telephones (3.4 bn [2007]), fixed-line telephones (1.2 bn [2005]), televisions (1.4 bn [2003]), and radios (2.5 bn [2003]) (Nationmaster, 2009). The total E-waste production, 11.7 million tonnes per year, is similar to the above calculation of the E-waste produced in rich countries. Again, the total global E-waste production will be considerably higher because some of the data are six years old. Similarly, the mass of WEEE produced will be higher because it includes heavy electrical items, such as refrigerators and air conditioning units.

Adjusting the calculated figure of 13.9 million tonnes per year for the 20% growth in the World's Gross Domestic Product (GDP) over the last five years, gives 16.8 million tonnes. Given that computers form the bulk of E-waste and that most E-waste is produced in rich countries (Cobbing, 2008), it is probable that the actual global E-waste production is 20–25 million tonnes per year, at the lower end of the United Nations Environment Programme's (UNEP's) estimation of 20–50 million tonnes per year (UNEP, 2006).

2.2. Future trends in E-waste production

The global production of E-waste will change as economies grow and new technologies are developed. For any given country, the total number of computers and other potential E-waste items is strongly correlated with the country's GDP, because electrical and electronic items are essential for the functioning of all but the most primitive economies. Fig. 1 shows the total number of computers per country as a function of that country's GDP. Fig. 1 supports the supposition that economic growth will result in more E-waste production. However, assessing the effect of economic growth on the total E-waste production from Fig. 1 is difficult because there is considerable scatter and no weighting according to the country's population. A better measure of the distribution of computers, and by implication E-waste production, is their distribution amongst the Earth's population as a function of wealth (Fig. 2), defined here as GDP per person weighted for Purchasing Power Parity (PPP). Fig. 2 shows that there is an exponential relationship between wealth and number of computers and that the richest billion people have 75% of all computers. Fig. 2 indicates that the number of computers per 100 people, and hence the total number of computers, will increase faster in richer countries than in poor countries for any given increase in GDP. This is in agreement with the predictions of Hischier et al. (2005), who reported that the annual growth of E-waste in Europe is increasing at a rate of 3–5%, compared to an average (2005–2008) increase in GDP of 2.6%. If the number of computers is indicative of total E-waste production, then Eastern Europe, Latin America and China will become major E-waste producers in the next 10 years.

Changes in technology will also affect the global mass of E-waste produced. Short innovation cycles of hardware have led to a high turnover of devices. The lifespan of central processing units in computers dropped from 4–6 years in 1997 to 2 years in 2005 (Babu et al., 2007).

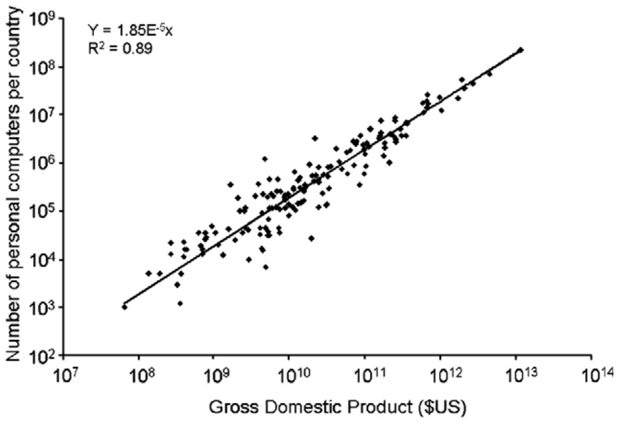

Fig. 1. Number of personal computers per country as a function of GDP for 161 countries. (Sources: CIA, 2009b; Nationmaster, 2009).

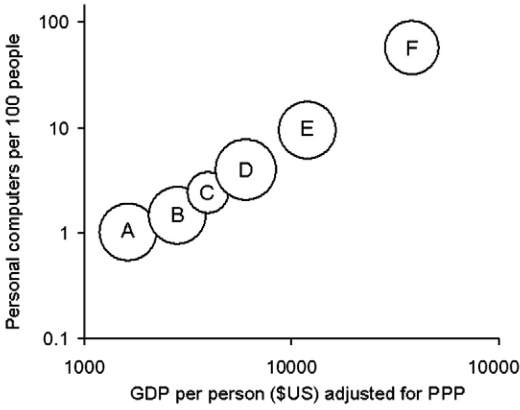

Fig. 2. Number of personal computers per 100 people as a function of Gross Domestic Product adjusted for Purchasing Power Parity for each billion of the Earth's inhabitants. Note that the size of the bubble is proportional to the number of inhabitants. (Sources: CIA, 2009a; Nationmaster, 2009).

	Population (bn)	Dominant geographic regions
A	1.30	Sub-Saharan Africa, Bangladesh, Pakistan
B	1.17	India
C	0.66	South East Asia
D	1.33	China
E	0.98	Eastern Europe, Latin America
F	1.27	Western Europe, United States, Australasia

The average mass of 25 kg for a personal computer (Table 1) is indicative of a desktop computer with a Cathode Ray Tube (CRT) monitor, which represents most of the past and present computers in the E-waste stream. However, the advent of Liquid Crystal Displays (LCD) will reduce the average weight of a desktop. More significantly, the increasing prevalence of laptop and netbook computers (Micklethwait, 2009a), which weigh just 1–3 kg, will significantly reduce the average mass of a discarded computer. In the case of netbooks, computing power and associated potential E-waste production has been shifted from the end user to remote computing “clouds”, supported by warehouses of shared machines, which may be located in another country (Micklethwait, 2009b). There is a lacuna of information on E-waste generation from these computing warehouses. E-waste growth from increasing wealth and shorter innovation cycles may be offset by miniaturisation and outsourcing of computing power.

3. Potential environmental contaminants associated with E-waste

The chemical composition of E-waste varies depending on the age and type of the discarded item. However, most E-waste is composed of a mixture of metals, particularly Cu, Al, and Fe, attached to, covered with, or mixed with various types of plastics and ceramics (Hoffmann, 1992). A discarded personal computer with a CRT monitor typically weighs 25 kg and consists of metal (43.7%), plastics (23.3%), electronic components (17.3%) and glass (15%) (Berkhout and Hertin, 2004). Heavy WEEE items, such as washing machines and refrigerators, which are mostly composed of steel, may contain fewer potential environmental contaminants than lighter E-waste items, such as laptop computers, which may contain high concentrations of flame retardants and heavy metals.

Virtually all E-waste contains some valuable components or base materials, especially Cu. These are environmentally important, because they provide an incentive for recycling, which occurs predominantly in poor countries, and may result in a human health risk or environmental pollution. Platinum group metals are included in electrical contact materials due to their high chemical stability and conductance of electricity. The precious metal concentrations in printed circuit boards is more than tenfold higher than commercially-mined minerals (Betts, 2008a).

Table 2 lists the potential environmental contaminants associated with E-waste. Some contaminants, such as heavy metals, are used in the manufacture of electronic goods, while others, such as polycyclic aromatic hydrocarbons (PAHs) are generated by the low-temperature combustion of E-waste. The burning of insulated wire, which typically occurs in open iron barrels, generates 100 times more dioxins than burning domestic waste (Gullett et al., 2007).

The concentrations of environmental contaminants found in E-waste depend on the type of item that is discarded and the time when that item was produced. E-waste composition is spatially and temporally heterogeneous. Table 2 gives the concentrations of some components in Swiss E-waste (Morf et al., 2007). Concentrations of Cd, Cu, Ni, Pb and Zn are such that were these elements released into the environment they would pose a risk to ecosystems and human health (Wilmoth et al., 1991). Using the estimation that 20 million tonnes of E-waste are produced annually, combined with the data of Morf et al. (2007), the amounts of some potential contaminants that are contained in the annual E-waste stream have been calculated (Table 2). Although recycling may remove some contaminants, large amounts may still end up concentrated in landfills or E-waste recycling centres, where they may adversely affect human health or the environment. Some 820,000 t of Cu are included in the annual flow of E-waste. Despite recycling, it would seem E-waste is a major contributor to the some 5000 t of Cu emitted into the environment annually (Bertram et al., 2002).

Polybrominated diphenyl ethers (PBDEs) are flame retardants that are mixed into plastics and components. There are no chemical bonds between the PBDEs and the plastics and therefore they may leach from the surface of E-waste components into the environment (Deng et al., 2007). PBDEs are lipophilic, resulting in their bioaccumulation in organisms and biomagnification in food chains (Deng et al., 2007). PBDEs have endocrine disrupting properties (Tseng et al., 2008).

Obsolete refrigerators, freezers and air conditioning units contain ozone-depleting Chlorofluorocarbons (CFCs). These gases may escape from items disposed in landfills (Scheutz et al., 2004).

3.1. Unusual contaminants in E-waste

E-waste may contain complex mixtures of potential environmental contaminants that are distinct from other forms of waste. Some potential contaminants in E-waste are uncommon, even in other contaminated sites. Consequently, there has been little work on their environmental effects. Examples include Li (batteries), Be (contact material), Sb (flame retardant) (Ernst et al., 2003), and Ga and In (used in Si chips and LCD monitors) (Ladou and Lovegrove, 2008).

3.2. Changing nature of E-waste

E-waste composition is changing with technological development and pressure on manufacturers from regulators and NGOs. The replacement of CRT monitors with LCD displays will reduce the concentration of Pb in E-waste, as each CRT tube contains some 2 kg Pb (Puckett et al., 2005). However, LCD displays contain Hg (Mester et al., 2005), In, Sn and Zn (Li et al., 2009). Similarly, fibre optics, which may replace some Cu wires (Berkhout and Hertin, 2004), can contain F, Pb, Y and Zr (Kogo et al., 1995). Rechargeable battery composition has also changed dramatically, from old Ni–Cd, to Ni metal hydrides, to Li ion batteries.

NGOs have placed pressure on manufacturers to reduce or eliminate the content of potential environmental contaminants in their products. Manufacturers are competing to be seen as “green” and want to remove as many toxic chemicals from products as possible (Betts, 2008b). Many producers of electronic and electrical goods have responded to pressure from NGOs and the public and are investigating innovative ways to enhance safe disposal and recycling. For example, radio frequency identification tags cost 10–20 cents and

Table 2
Potential environmental contaminants arising from E-waste disposal or recycling.

Contaminant	Relationship with E-waste	Typical E-waste concentration (mg/kg)[a]	Annual global emission in E-waste (tons)[b]
Polybrominated diphenyl ethers (PBDEs) polybrominated biphenyls (PBBs) tetrabromobisphenol-A (TBBPA)	Flame retardants		
Polychlorinated biphenyls (PCB)	Condensers, transformers	14	280
Chlorofluorocarbon (CFC)	Cooling units, insulation foam		
Polycyclic aromatic hydrocarbons (PAHs)	Product of combustion		
Polyhalogenated aromatic hydrocarbons (PHAHs)	Product of low-temperature combustion		
Polychlronated dibenzo-*p*-dioxins (PCDDs), polychlorinated dibenzofurans (PCDFs)	Product of low-temperature combustion of PVCs and other plastics		
Americium (Am)	Smoke detectors		
Antimony	Flame retardants, plastics (Ernst et al., (2003))	1700	34,000
Arsenic (As)	Doping material for Si		
Barium (Ba)	Getters in cathode ray tubes (CRTs)		
Beryllium (Be)	Silicon-controlled rectifiers		
Cadmium (Cd)	Batteries, toners, plastics	180	3600
Chromium (Cr)	Data tapes and floppy disks	9900	198,000
Copper (Cu)	Wiring	41,000	820,000
Gallium (Ga)	Semiconductors		
Indium (In)	LCD displays		
Lead (Pb)	Solder (Kang and Schoenung, (2005)), CRTs, batteries	2900	58,000
Lithium (Li)	Batteries		
Mercury (Hg)	Fluorescent lamps, batteries, switches	0.68	13.6
Nickel (Ni)	Batteries	10,300	206,000
Selenium (Se)	Rectifiers		
Silver (Ag)	Wiring, switches		
Tin (Sn)	Solder (Kang and Schoenung, (2005)), LCD screens	2400	48,000
Zinc (Zn)		5100	102,000
Rare earth elements	CRT screens		

Adapted from (e-waste, 2009).

[a] (Morf et al., 2007).

[b] Assuming a global e-waste production of 20 million tonnes per year.

provide information about the condition and composition of computer systems and other electronics products (Betts, 2008a). Such tags can alert waste managers and recyclers to valuable components and potential environmental contaminants contained within the end-of-life product (Binder et al., 2008).

Producing halogen-free components would reduce polychlorinated biphenyls (PCBs) and dioxin loadings in E-waste; however, their production is more environmentally costly (Bergendahl et al., 2004). Brominated flame retardants can be replaced with more environmentally friendly phosphorus-based retardants (Dietz et al., 2004) such as aminophenyl phosphate (Mauerer, 2005). Lead-free solder could significantly reduce the environmental burden of this toxic heavy metal (Bradley, 2003); this may be enshrined in law (Herat, 2008) in many countries. In 2003, the European Union enacted the Restriction on Hazardous Substances Directive (RoHS), limiting the concentrations in homogeneous electronic materials of Pb, Hg, Cr (IV), polybrominated biphenyls (PBBs) and PBDEs to 1000 mg/kg, and Cd to 100 mg/kg (LaDou, 2006). RoHS was met with some resistance by manufacturers due to compliance costs and technical problems, such as the use of low-Pb solders that are prone to "tin whisker" growth (Puttlitz and Galyon, 2007).

4. The flux of these contaminants on a global scale: the fate of E-waste

Most E-waste is not recycled, because E-waste items tend to go out with household waste and receive no special treatment (Ladou and Lovegrove, 2008). Of that which is collected, some 80% is exported to poor countries (Schmidt, 2006).

Electronic equipment that is no longer of use to the original purchaser may be reused, effectively extending its lifespan. Reuse is ultimately the source of some E-waste in many poor countries (Puckett et al., 2005) that accept donations of equipment considered obsolete in rich countries. Old yet functional electronic equipment is often shipped to developing countries by well-meaning donors in the West. Unscrupulous organisations in rich countries use donations of obsolete electronic equipment as a loop-hole in the Basel Convention to export both functioning and non-functioning electronic equipment (Ladou and Lovegrove, 2008). Brokers who arrange the export of functioning products often pad shipping containers with irreparable waste, which may account for up to 75% of deliveries. Most of this ends up in landfills and informal dumps (Schmidt, 2006).

China receives some 70% of all exported E-waste (Liu et al., 2006), while significant quantities are also exported to India, Pakistan, Vietnam, the Philippines, Malaysia, Nigeria and Ghana (Puckett et al., 2005), and possibly to Brazil and Mexico. Due to the semi-clandestine nature of these operations, the actual mass of E-waste being exported is impossible to quantify. Some 500 shipping containers filled with electronic items pass through Lagos each month (Schmidt, 2006). NGOs such as Greenpeace campaign against this "hidden flow" of E-waste (Cobbing, 2008).

5. Disposal and recycling of E-waste and associated environmental contamination

Most E-waste is currently landfilled (Barba-Gutierrez et al., 2008). Using the Toxicity Characteristic Leaching Procedure (TCLP) (USEPA, 2000), Spalvins et al. (2008) concluded that E-waste disposal in modern-municipal solid waste landfills is unlikely to result in lead leachate concentrations of regulatory concern. However, Dagan et al. (2007) demonstrated that the chemical cocktail that leached from a variety of consumer electronics using TCLP was toxic to aquatic organisms. Incineration prior to landfilling may increase the mobility of heavy metals, particularly Pb (Gullett et al., 2007). On average the plastic fraction of E-waste has Sn, Pb, Ni, Zn and Sb concentrations >1000 mg/kg as well as >100 mg/kg Cd (Morf et al., 2007). While contained in a plastic matrix, these elements do not leach and are not bioavailable. However, combustion or dissolution will liberate these elements. As with other materials, leaching of many heavy metals such as Pb from E-waste is increased at low pH and in the presence of organic ligands (Jang and Townsend, 2003).

Most studies investigating leaching from landfilled E-waste have investigated just a few key contaminants, especially Pb. However, there is a lacuna of information on the behaviour of oxyanion forming contaminants such as Sb, which can occur at concentrations >1000 mg/kg in some E-waste components (Morf et al., 2007). Antimonate ($Sb(OH)_6^-$) has been shown to be more mobile and more toxic in soil than Pb, and is more soluble at higher pH values and readily taken up by plants (Tschan et al., 2009).

Niu and Li (2007) showed that compaction of E-waste, prior or during landfilling, can increase leaching through the disruption of circuit board components. The same authors showed that cement solidification, which imparts impact resistance, raises pH and reduces water flux through the waste, reduced Pb leaching from E-waste to below regulatory levels.

5.1. Recycling

E-waste recycling involves the disassembly and destruction of the equipment to recover new materials (Cui and Zhang, 2008). Recycling can recover 95% of the useful materials from a computer and 45% of materials from cathode ray tube monitors (Ladou and Lovegrove, 2008). In rich countries, such as Japan, high tech recycling operations function well with little environmental impact (Aizawa et al., 2008). Modern techniques can recover high-Pb glass from discarded CRT with minimal environmental impact (Andreola et al., 2007). Any ecological benefits of recycling are more than offset if the waste has to be transported long distances due to the negative environmental effects of fossil fuel combustion (Barba-Gutierrez et al., 2008). However, recycling always has a lower ecological impact than landfilling of incinerated E-waste (Hischier et al., 2005).

Mechanical separation of components is the first step in E-waste recycling. Components may be separated for reuse or metallurgical processing (He et al., 2006). This process can be automated or carried out by hand. In poor countries, there is a risk that children may be employed to separate E-waste components (Ladou and Lovegrove, 2008). An open flame is often used to free components (Manomaivibool, 2009), which may result in exposure to volatilised contaminants.

Valuable metals may be recovered from E-waste by pyro- hydro- and bio-metallurgical processes (Cui and Zhang, 2008). Pyrometallurgical processing includes incineration of the matrix and smelting of the target metals. The efficacy of this process depends on investment. Shoddy operations have the potential to emit dangerous compounds into the environment. Copper is a catalyst for dioxin formation when flame retardants are incinerated, in particular the low-temperature incineration of brominated flame retardants (Cui and Zhang, 2008). Hydrometallurgical processes involve the dissolution and recovery of the target metals with acids, cyanide, halides, thiourea or thiosulphate.

Presently limited to rich countries, bio-metallurgical processing is attractive due to its low-cost and high specificity for the target elements (Cui and Zhang, 2008). Brandl et al. (2001) showed how *Thiobacilus* bacteria and fungi (*Aspergillus niger*, *Penicillium simplicissimum*) could facilitate metal leaching from electronic scrap. Creamer et al. (2006) employed *Desulfovibrio desulfuricans* to recover Au, Pt and Cu from E-waste.

6. Environments contaminated by E-waste

6.1. Case study: Guiyu and some other E-waste recycling centres

The city of Guiyu with its surrounding towns in the Guangdong region of China is the largest E-waste recycling site in the world.

Recycling has been occurring since 1995 (Wong et al., 2007). Guiyu has a population of 150,000, most of which are immigrants. Nearly 80% of families have members who have engaged in E-waste recycling operations (Li et al., 2008a). Wind carries particulate matter from Guiyu to the Pearl River Delta Region, which has a population of some 45 million people (Deng et al., 2007). Villagers and migrant workers use environmentally unsound techniques to recycle E-waste. These include the heating and manual removal of components from printed circuit boards, open burning to reduce volumes and recover metals, and open acid digestion of E-waste to recover precious metals. The waste-acid, rich in heavy metals, is then discarded onto the soil or into waterways. Solder is melted from printed circuit boards over makeshift coal grills. Portable household fans are the only precautionary measures taken to reduce worker exposure to toxic solder fumes (Leung et al., 2008). Workers toil without goggles, masks or gloves (Li et al., 2008a). These crude recycling techniques have resulted in widespread environmental contamination with some of the components listed in Table 2.

6.2. Waters and aquatic systems

E-waste contaminants can enter aquatic systems via leaching from dumpsites where processed or unprocessed E-waste may have been deposited. Similarly, the disposal of acid following hydrometallurgical processes into waters or onto soils, as well as the dissolution or settling of airborne contaminants, can also result in the contamination of aquatic systems. Luo et al. (2007b) reported that carp from the Nanyang river, near Guiyu, were bioaccumulating PBDEs to concentrations of up to 766 ng/g (fresh weight). Unsurprisingly, the same authors (Luo et al., 2007a) reported elevated PBDE concentrations in the sediments (up to 16,000 ng/g) of the same river. In an aquatic ecosystem near an E-waste recycling plant, Wu et al. (2008) reported that the water snake, the top predator, had on average 16,512 ng/g PCBs and 1091 ng/g PBDEs on a wet weight basis. Mud carp, crucian carp and prawns from the same area also had elevated concentrations of these contaminants. The ambient water contained just 204 ng/L PCBs. Waterfowl from downstream areas in the Pearl River Delta also contained elevated PCB and PBDEs (Luo et al., 2009a). Brominated flame retardants other than PBDE, namely 1,2-bis(2,4,6-tribromophenoxy)ethane, decabromodiphenyl ethane and tetrabromobisphenol A bis (2,3-dibromopropyl) ether, are widespread in various biota of the Pearl River Delta, downstream from E-waste recycling towns (Shi et al., 2009).

Wang and Guo (2006) found up to 0.4 mg/L Pb in river water downstream of a recycling plant in Guiyu, some 8 times higher than the local drinking water standard (0.05 mg/L). Similarly, Wong et al. (2007) reported elevated concentrations of Ag, Cr, Li, Mo, Sb and Se in the nearby Lianjiang river.

6.3. Air

Many E-waste contaminants are spread into the air via dust. This is a major exposure pathway for humans through ingestion, inhalation and skin absorption (Mielke and Reagan, 1998). Air samples taken near Guiyu contained polychlorodibenzo-p-dioxins between 65 and 2765 pg/m^3, the highest level of atmospheric dioxins ever reported (Li et al., 2007).

Combustion of E-waste containing flame retardants has resulted in concentrations of total PBDEs of up to 16,575 pg/m^3 in aerial samples near Guiyu, some 300 times higher than in nearby Hong Kong (Deng et al., 2007). Aerial contamination of PBDEs in the city of Guiyu exceeds 11,000 pg/m^3 during the daytime, dropping to under 5000 pg/m^3 at night (Chen et al., 2009a). Similarly, high aerial concentrations of particulate PAHs, Cr, Cu and Zn have also been reported (Deng et al., 2006). Leung et al. (2008) reported concentrations of over 2% Pb and several thousand mg/kg Cu and Zn in dust the roads in Guiyu. Dust collected from E-waste recycling workshops had Pb, Cu and Zn concentrations some fivefold higher than road dust. Ha et al. (2009) showed that E-waste workers in Bangalore breathe dust-laden air containing Cd, In, Sn, Sb, Pb and Bi at concentrations of 1.5, 1.3, 91, 13, 89 and 1.0 ng/m^3 respectively.

6.4. Soils and terrestrial environments

Soils from a site where acid leaching was used to recover valuable metals, contained up to 4250 ng/g PBDEs (Leung et al., 2007). There are elevated concentrations of PCBs, PAHs (Shen et al., 2009a) and PBDEs (Cai and Jiang, 2006) in Chinese agricultural soils proximal to E-waste reprocessing sites. Luo et al. (2009b) reported PBDE concentrations of 191 to 9156 ng/g (dry weight) in farmland soils 2 km from an E-waste recycling workshop. Soils from this region also contain polychlronated dibenzo-*p*-dioxins and dibenzofurans (PCDD/Fs), PCBs and PAHs at concentrations up to 100, 330 and 20,000 ng/g, respectively (Shen et al., 2009b).

Liu et al. (2008) reported elevated concentrations of PBDEs and PCBs in soils, plants and snails from the town of Guiyu and the surrounding areas. PBDEs are translocated from soils to plants. Leaves of bracken fern (*Pteridium aquilinum* L.), spider fern (*Pteris multifida* Poir.), sorghum (*Sorghum bicolour* L.), Japanese dock (*Rumex japonicus* Houtt.) and Eastern daisy fleabane (*Erigeron annuus* L.) contained PBDEs at concentrations of 144, 116, 162, 278 and 326 ng/g (dry matter), respectively, when growing in soil containing 25,479 ng/g PBDE (Yang et al., 2008). Although the bioaccumulation coefficients are small (<0.01) plant uptake may facilitate the entry of these contaminants into food chains.

Soils at an E-waste recycling slum in Bangalore contained up to 39 mg/kg Cd, 4.6 mg/kg In, 957 mg/kg Sn, 180 mg/kg Sb 49 mg/kg Hg, 2850 mg/kg Pb, and 2.7 mg/kg Bi (Ha et al., 2009). These concentrations are some one-hundredfold higher than those found at a nearby control site in the same city.

Analysis of rice samples from another E-waste processing town in Eastern China, Taizhou (Zhejiang province) revealed concentrations of Pb and Cd in polished rice to be 2–4 times in excess of 0.2 mg/kg, the maximum allowable concentrations of these elements in foodstuffs in China (Fu et al., 2008). In the same town, Liang et al. (2008) measured elevated levels (up to 18 ng/g) of PBDEs in chicken tissues and concluded that these toxins may pose a threat to humans and ecosystems. Rice paddy soils adjacent to E-waste recycling areas in the Zhejiang province were shown to reduce the germination rate of rice (Zhang and Min, 2009). A micronuclei assay using *Vicia fabia* indicated that the contaminants in these soils also promote DNA damage.

6.5. Humans

Aerial contamination with dioxins at Guiyu has resulted in levels of human exposure some 15–56 times the WHO recommended maximum intake (Chatterjee, 2007). Elevated levels of dioxins were found in human milk, placentas and hair, indicating that dioxins are being taken up by humans, from the air, water, or foodstuffs, at sufficient levels to pose a serious health risk (Chan et al., 2007).

The transfer of E-waste derived PCBs to ground and surface-waters, agricultural soils, rice, eggs, fish and ultimately humans has been demonstrated (Zhao et al., 2006). E-waste workers and other residents from Guiyu had median blood serum BPDE concentrations of 126 ng/L and 35 ng/L, respectively, compared to referents from a nearby town who had just 10 ng/L (Qu et al., 2007). Samples of human hair from towns near Taizhou contained PBBs, PBDEs and PCBs at concentrations up to 58 ng/g, 30 ng/g and 182 ng/g, respectively (Zhao et al., 2008).

Children in Guiyu had significantly higher blood Pb (Huo et al., 2007; Li et al., 2008b) and Cd (Zheng et al., 2008) levels and lower cognitive abilities than children from a nearby control town (Li et al., 2008b). Similarly, lactating residents of Guiyu had elevated concentrations of PCBs in their breast milk (Xing et al., 2009). This could not be attributed to a single exposure pathway, since people are exposed PCBs through many enriched foodstuffs, drinking water sources and occasional air contamination.

Li et al. (2008a) reported elevated levels of Cr (median 0.094 mg/L) in umbilical cord blood from infants in Guiyu. Umbilical cord Cr concentrations were correlated with DNA damage and were correlated as well with the mother's exposure to E-waste recycling. However, it was unclear whether Cr or some other toxic agent associated with E-waste resulted in DNA damage. Liu et al. (2009) reported that E-waste recycling workers from villages in the Jinghai county had chromosomal aberrations at a rate some 20-fold higher than villagers not exposed to E-waste. The authors conclude that E-waste is a potential source of genetic mutation and may induce cytogenetic damage within the general population exposed to E-waste pollution.

7. The re-exportation of contaminants associated with E-waste: the other hidden flow

E-waste recycling as conducted in Guiyu results in the contamination of the entire region, pervading the water, air, soil and biota contained therein. Although exports to poor countries are impossible to quantify, even a small fraction of the global E-waste stream would contribute hundreds of tonnes of Pb and several tonnes of Cd, Hg and PCBs. Therefore, other products that are manufactured in E-waste processing regions may contain elevated levels of E-waste associated contaminants. Some of these products may be consumed locally. However, others may be exported to national or international markets. Weidenhamer and Clement (2007a) found evidence that Pb from E-waste was being incorporated into Chinese-manufactured jewellery for export to the United States. Wipe tests showed that this lead was potentially available for human absorption (Weidenhamer and Clement, 2007b).

Reports abound of children's toys, imported from China, which contain elevated levels of lead or brominated flame retardants (Chen et al., 2009b). Although the authors did not link the source of the contaminants to E-waste, it is conceivable that recycled materials from E-waste, which may contain PBDEs or PCBs, are used in the manufacture of products for export.

Zhao et al. (2009) found that polyhalogenated aromatic hydrocarbons (PHAHs) occurred in elevated concentrations in the foodstuffs produced in an E-waste processing region in the Zhejiang province of China. Ultimately, some of these food products may be exported, posing an international health risk. Regular screening tests may not detect some of the unusual contaminants associated with E-waste. The risk of re-exportation of E-waste contaminants warrants further investigation.

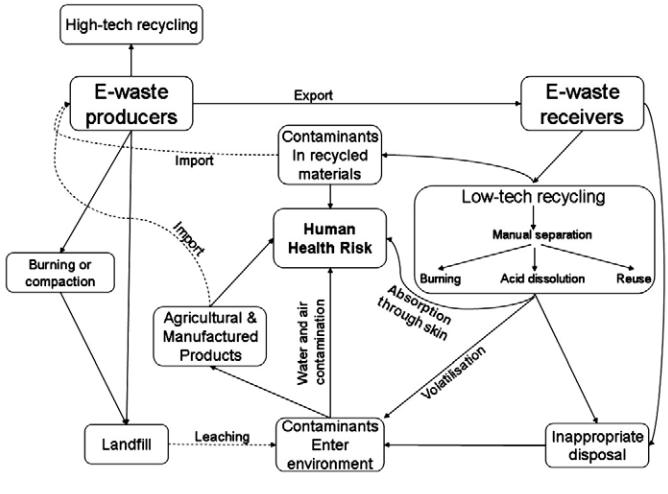

Fig. 3. Fluxes of contaminants associated with E-waste from producers to receivers and ultimately to humans.

Fig. 3 shows the fluxes of contaminants associated with E-wastes from producers to receivers and ultimately to humans. The fluxes shown in Fig. 3 are relevant at a range of scales, both national and international. Fig. 3 shows that, potentially, E-waste may affect the whole of humanity.

8. Conclusions

E-waste is omnipresent. It is characterised by its unusual chemical composition and the difficulties associated with determining its mass and flux at both local and global scales. Contamination associated with E-waste has already caused considerable environmental degradation in poor countries and negatively affected the health of the people who live there. Cleansing of such large contaminated sites is probably unfeasible, since they have been heavily contaminated with numerous contaminants, many of which are poorly studied. However, the negative effects of the contaminants at these sites may be reduced using standard remediation technologies. There is limited knowledge on the ecological effects, human health risks and remediation options for some E-waste contaminants, such as Li and Sb, since they are not normally environmental pollutants. Rich countries have self-interest in mitigating the negative environmental effects of E-waste because it will negatively affect the quality and quantity of food and manufactured goods that are imported from poor countries.

List of abbreviations

CFC	Chlorofluorocarbon
CRT	Cathode Ray Tube
GDP	Gross Domestic Product
LCD	Liquid Crystal Display
NGO	Non Governmental Organisation
PAH	polycyclic aromatic hydrocarbon
PBB	polybrominated biphenyl
PBDE	polybrominated diphenyl ether
PCB	polychlorinated biphenyl
PCDD	polychlronated dibenzo-*p*-dioxin
PCDF	polychlronated dibenzofuran
PHAH	polyhalogenated aromatic hydrocarbon
PPP	Purchasing Power Parity
RoHS	Restriction on Hazardous Substances Directive
TCLP	Toxicity Characteristic Leaching Procedure
UNEP	United Nations Environment Programme
WEEE	Waste Electrical and Electronic Equipment

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References

Aizawa H, Yoshida H, Sakai SI. Current results and future perspectives for Japanese recycling of home electrical appliances. Res Conserv Recycl 2008;52:1399–410.

Andreola F, Barbieri L, Corradi A, Ferrari AM, Lancellotti I, Neri P. Recycling of EOL CRT glass into ceramic glaze formulations and its environmental impact by LCA approach. Int J Life Cycle Assess 2007;12:448–54.

Babu BR, Parande AK, Basha CA. Electrical and electronic waste: a global environmental problem. Waste Manag Res 2007;25:307–18.

Barba-Gutierrez Y, Adenso-Diaz B, Hopp M. An analysis of some environmental consequences of European electrical and electronic waste regulation. Res Conserv Recycl 2008;52:481–95.

Bergendahl CG, Lichtenvort K, Johansson G, Zackrisson M, Nyyssonen J. Environmental and economic implications of a shift to halogen-free printed wiring boards. Electronics Goes Green 2004 (Plus): Driving Forces for Future Electronics Proceedings; 2004. p. 783–8.

Berkhout F, Hertin J. De-materialising and re-materialising: digital technologies and the environment. Futures 2004;36:903–20.

Bertram M, Graedel TE, Rechberger H, Spatari S. The contemporary European copper cycle: waste management subsystem. Ecol Econ 2002;42:43–57.

Betts K. Producing usable materials from e-waste. Environ Sci Technol 2008a;42:6782–3.

Betts K. Reducing the global impact of e-waste. Environ Sci Technol 2008b;42: 1393-1393.

Binder CR, Quirici R, Domnitcheva S, Staubli B. Smart labels for waste and resource management — an integrated assessment. J Ind Ecol 2008;12:207–28.

Bradley E. Lead-free solder assembly: impact and opportunity. 53rd Electronic Components & Technology Conference, 2003 Proceedings; 2003. p. 41–6.

Brandl H, Bosshard R, Wegmann M. Computer-munching microbes: metal leaching from electronic scrap by bacteria and fungi. Hydrometallurgy 2001;59:319–26.

Cai ZW, Jiang GB. Determination of polybrominated diphenyl ethers in soil from e-waste recycling site. Talanta 2006;70:88–90.

Chan JKY, Xing GH, Xu Y, Liang Y, Chen LX, Wu SC, et al. Body loadings and health risk assessment of polychlorinated dibenzo-p-dioxins and dibenzofurans at an intensive electronic waste recycling site in China. Environ Sci Technol 2007;41:7668–74.

Chatterjee R. E-waste recycling spews dioxins into the air. Environ Sci Technol 2007;41: 5577-5577.

Chen DH, Bi XH, Zhao JP, Chen LG, Tan JH, Mai BX, et al. Pollution characterization and diurnal variation of PBDEs in the atmosphere of an E-waste dismantling region. Environ Pollut 2009a;157:1051–7.

Chen SJ, Ma YJ, Wang J, Chen D, Luo XJ, Mai BX. Brominated flame retardants in children's toys: concentration, composition, and children's exposure and risk assessment. Environ Sci Technol 2009b;43:4200–6.

CIA. Country Comparison: GDP — per capita (PPP). Cent Intel Agency 2009a.

CIA. Country Comparison: GDP (purchasing power parity). Cent Intel Agency 2009b.

Cobbing M. Toxic Tech: Not in Our Backyard. Uncovering the Hidden Flows of e-waste. Report from Greenpeace International. http://www.greenpeace.org/raw/content/belgium/fr/press/reports/toxic-tech.pdf, Amsterdam, 2008.

Creamer NJ, Baxter-Plant VS, Henderson J, Potter M, Macaskie LE. Palladium and gold removal and recovery from precious metal solutions and electronic scrap leachates by Desulfovibrio desulfuricans. Biotechnol Lett 2006;28:1475–84.

Cui JR, Zhang LF. Metallurgical recovery of metals from electronic waste: a review. J Hazard Mater 2008;158:228–56.

Dagan R, Dubey B, Bitton G, Townsend T. Aquatic toxicity of leachates generated from electronic devices. Arch Environ Contam Toxicol 2007;53:168–73.

Deng WJ, Louie PKK, Liu WK, Bi XH, Fu JM, Wong MH. Atmospheric levels and cytotoxicity of PAHs and heavy metals in TSP and PM2.5 at an electronic waste recycling site in southeast China. Atmos Environ 2006;40:6945–55.

Deng WJ, Zheng JS, Bi XH, Fu JM, Wong MH. Distribution of PBDEs in air particles from an electronic waste recycling site compared with Guangzhou and Hong Kong, South China. Environ Int 2007;33:1063–9.

Dietz M, Horold S, Nass B, Schacker O, Schmitt E, Wanzke W. New environmentally friendly phosphorus based flame retardants for printed circuit boards as well as polyamides and polyesters in E&E applications. Electronics Goes Green 2004 (Plus): Driving Forces for Future Electronics Proceedings; 2004. p. 771–6.

e-waste. Hazardous Substances in e-Waste. A Knowledge Base for the Sustainable Recycling of E-Waste. E-Waste: A Swiss E-Waste Guide; 2009.

Ernst T, Popp R, Wolf M, van Eldik R. Analysis of eco-relevant elements and noble metals in printed wiring boards using AAS, ICP-AES and EDXRF. Anal Bioanal Chem 2003;375:805–14.

Fu JJ, Zhou QF, Liu JM, Liu W, Wang T, Zhang QH, et al. High levels of heavy metals in rice (Oryza sativa L.) from a typical E-waste recycling area in southeast China and its potential risk to human health. Chemosphere 2008;71:1269–75.

Goosey M. End-of-life electronics legislation — an industry perspective. Circuit World 2004;30:41–5.

Gullett BK, Linak WP, Touati A, Wasson SJ, Gatica S, King CJ. Characterization of air emissions and residual ash from open burning of electronic wastes during simulated rudimentary recycling operations. J Mater Cycl Waste Manag 2007;9:69–79.

Ha NN, Agusa T, Ramu K, Tu NPC, Murata S, Bulbule KA, et al. Contamination by trace elements at e-waste recycling sites in Bangalore, India. Chemosphere 2009;76: 9-15.

He WZ, Li GM, Ma XF, Wang H, Huang JW, Xu M, et al. WEEE recovery strategies and the WEEE treatment status in China. J Hazard Mater 2006;136:502–12.

Herat S. Green electronics through legislation and lead free soldering. Clean-Soil Air Water 2008;36:145–51.

Hilty LM. Electronic waste — an emerging risk? Environ Impact Assess Rev 2005;25:431–5.

Hischier R, Wager P, Gauglhofer J. Does WEEE recycling make sense from an environmental perspective? The environmental impacts of the Swiss take-back and recycling systems for waste electrical and electronic equipment (WEEE). Environ Impact Assess Rev 2005;25:525–39.

Hoffmann JE. Recovering precious metals from electronic scrap. J-J Mines Met Mater Soc 1992;44:43–8.

Huisman J, Magalini F. Where are WEEE now? Lessons from WEEE: Will EPR work for the US? Proceedings of the 2007 IEEE International Symposium on Electronics & the Environment, Conference Record; 2007. p. 149–54.

Huo X, Peng L, Xu XJ, Zheng LK, Qiu B, Qi ZL, et al. Elevated blood lead levels of children in Guiyu, an electronic waste recycling town in China. Environ Health Perspect 2007;115:1113–7.

Jang YC, Townsend TG. Leaching of lead from computer printed wire boards and cathode ray tubes by municipal solid waste landfill leachates. Environ Sci Technol 2003;37:4778–84.

Kang HY, Schoenung JM. Electronic waste recycling: a review of US infrastructure and technology options. Res Conserv Recycl 2005;45:368–400.

Kogo T, Kanamori H, Onishi M, Miyajima Y, Nakazawa M. Lead-containing fluoride glass, optical fiber and process for producing it. United States Patent office 1995; Patent Number 5432131.

Kohler A, Erdmann L. Expected environmental impacts of pervasive computing. Hu Ecol Risk Assess 2004;10:831–52.

LaDou J. Printed circuit board industry. Int J Hyg Environ Health 2006;209:211–9.

Ladou J, Lovegrove S. Export of electronics equipment waste. Int J Occup Environ Health 2008;14:1-10.

Leung AOW, Duzgoren-Aydin NS, Cheung KC, Wong MH. Heavy metals concentrations of surface dust from e-waste recycling and its human health implications in southeast China. Environ Sci Technol 2008;42:2674–80.

Leung AOW, Luksemburg WJ, Wong AS, Wong MH. Spatial distribution of polybrominated diphenyl ethers and polychlorinated dibenzo-p-dioxins and dibenzofurans in soil and combusted residue at Guiyu, an electronic waste recycling site in southeast China. Environ Sci Technol 2007;41:2730–7.

Li HR, Yu LP, Sheng GY, Fu JM, Peng PA. Severe PCDD/F and PBDQ/F pollution in air around an electronic waste dismantling area in China. Environ Sci Technol 2007;41: 5641–6.

Li JH, Gao S, Duan HB, Liu LL. Recovery of valuable materials from waste liquid crystal display panel. Waste Manag 2009;29:2033–9.

Li Y, Xu XJ, Liu JX, Wu KS, Gu CW, Shao G, et al. The hazard of chromium exposure to neonates in Guiyu of China. Sci Total Environ 2008a;403:99-104.

Li Y, Xu XJ, Wu KS, Chen GJ, Liu JX, Chen SJ, et al. Monitoring of lead load and its effect on neonatal behavioral neurological assessment scores in Guiyu, an electronic waste recycling town in China. J Environ Monitor 2008b;10:1233–8.

Liang SX, Zhao Q, Qin ZF, Zhao XR, Yang ZZ, Xu XB. Levels and distribution of polybrominated diphenyl ethers in various tissues of foraging hens from an electronic waste recycling area in South China. Environ Toxicol Chem 2008;27:1279–83.

Liu HX, Zhou QF, Wang YW, Zhang QH, Cai ZW, Jiang GB. E-waste recycling induced polybrominated diphenyl ethers, polychlorinated biphenyls, polychlorinated dibenzo-p-dioxins and dibenzo-furans pollution in the ambient environment. Environ Int 2008;34:67–72.

Liu Q, Cao J, Li KQ, Miao XH, Li G, Fan FY, et al. Chromosomal aberrations and DNA damage in human populations exposed to the processing of electronics waste. Environ Sci Pollut Res Int 2009;16:329–38.

Liu XB, Tanaka M, Matsui Y. Generation amount prediction and material flow analysis of electronic waste: a case study in Beijing, China. Waste Manag Res 2006;24:434–45.

Luo Q, Cai ZW, Wong MH. Polybrominated diphenyl ethers in fish and sediment from river polluted by electronic waste. Sci Total Environ 2007a;383:115–27.

Luo Q, Wong MH, Cai ZW. Determination of polybrominated diphenyl ethers in freshwater fishes from a river polluted by e-wastes. Talanta 2007b;72:1644–9.

Luo XJ, Zhang XL, Liu J, Wu JP, Luo Y, Chen SJ, et al. Persistent halogenated compounds in waterbirds from an e-waste recycling region in South China. Environ Sci Technol 2009a;43:306–11.

Luo Y, Luo XJ, Lin Z, Chen SJ, Liu J, Mai BX, et al. Polybrominated diphenyl ethers in road and farmland soils from an e-waste recycling region in Southern China: Concentrations, source profiles, and potential dispersion and deposition. Sci Total Environ 2009b;407:1105–13.

Manomaivibool P. Extended producer responsibility in a non-OECD context: the management of waste electrical and electronic equipment in India. Res Conserv Recycl 2009;53:136–44.

Mauerer O. New reactive, halogen-free flame retardant system for epoxy resins. Polym Degrad Stab 2005;88:70–3.

Mester A, Fraunholcz N, van Schaik A, Reuter MA. Characterization of the hazardous components in end-of-life notebook display. Light Met 2005;2005:1213–6.

Micklethwait J. Small but disruptive. The Economist; 2009a.

Micklethwait J. Unlocking the cloud. The Economist; 2009b.

Mielke HW, Reagan PL. Soil is an important pathway of human lead exposure. Environ Health Perspect 1998;106:217–29.

Morf LS, Tremp J, Gloor R, Schuppisser F, Stengele M, Taverna R. Metals, non-metals and PCB in electrical and electronic waste — actual levels in Switzerland. Waste Manag 2007;27:1306–16.

Nationmaster. Media Statistics. www.nationmaster.com accessed June 2009., 2009.

Niu XJ, Li YD. Treatment of waste printed wire boards in electronic waste for safe disposal. J Hazard Mater 2007;145:410–6.

OECD. OECD Environmental Outlook to 2030. 2009. Organisation for Economic Cooperation and Development http://213.253.134.43/oecd/pdfs/browseit/9708011E.PDF, 2008.

Puckett J, Westervelt S, Gutierrez R, Takamiya Y. The digital dump. Exporting re-use and abuse to Africa. Report from the Basel Action Network, Seattle, 2005.

Puttlitz KJ, Galyon GT. Impact of the ROHS Directive on high-performance electronic systems — Part II: key reliability issues preventing the implementation of lead-free solders. J Mater Sci: Mater Electron 2007;18:347–65.

Qu WY, Bi XH, Sheng GY, Lu SY, Fu H, Yuan J, et al. Exposure to polybrominated diphenyl ethers among workers at an electronic waste dismantling region in Guangdong, China. Environ Int 2007;33:1029–34.

Scheutz C, Mosbaek H, Kjeldsen P. Attenuation of methane and volatile organic compounds in landfill soil covers. J Environ Qual 2004;33:61–71.

Schmidt CW. Unfair trade — E-waste in Africa. Environ Health Perspect 2006;114: A232–5.

Shen C, Chen Y, Huang S, Wang Z, Yu C, Qiao M, et al. Dioxin-like compounds in agricultural soils near e-waste recycling sites from Taizhou area, China: Chemical and bioanalytical characterization. Environ Int 2009a;35:50–5.

Shen CF, Chen YX, Huang SB, Wang ZJ, Yu CN, Qiao M, et al. Dioxin-like compounds in agricultural soils near e-waste recycling sites from Taizhou area, China: chemical and bioanalytical characterization. Environ Int 2009b;35:50–5.

Shi T, Chen SJ, Luo XJ, Zhang XL, Tang CM, Luo Y, et al. Occurrence of brominated flame retardants other than polybrominated diphenyl ethers in environmental and biota samples from southern China. Chemosphere 2009;74:910–6.

Sinha-Khetriwal D, Kraeuchi P, Schwaninger M. A comparison of electronic waste recycling in Switzerland and in India. Environ Impact Assess Rev 2005;25:492–504.

Spalvins E, Dubey B, Townsend T. Impact of electronic waste disposal on lead concentrations in landfill leachate. Environ Sci Technol 2008;42:7452–8.

Tschan M, Robinson BH, Schulin R. Antimony in the soil-plant system — a review. Environ Chem 2009;6:106–15.

Tseng LH, Li MH, Tsai SS, Lee CW, Pan MH, Yao WJ, et al. Developmental exposure to decabromodiphenyl ether (PBDE 209): Effects on thyroid hormone and hepatic enzyme activity in male mouse offspring. Chemosphere 2008;70:640–7.

UNEP. Call for Global Action on E-waste. United Nations Environment Programme; 2006.

UNEP. Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal. United Nations Environment Programme. http://www.basel.int/, 2009.

USEPA. United States Environmental Protection Agency. Test Methods for Evaluating Solid Waste Method 1311SW-846, Washington, DC; 2000.

Wang JP, Guo XK. Impact of electronic wastes recycling on environmental quality. Biomed Environ Sci 2006;19:137–42.

Weidenhamer JD, Clement ML. Leaded electronic waste is a possible source material for lead-contaminated jewelry. Chemosphere 2007a;69:1111–5.

Weidenhamer JD, Clement ML. Widespread lead contamination of imported low-cost jewelry in the US. Chemosphere 2007b:67.

Widmer R, Oswald-Krapf H, Sinha-Khetriwal D, Schnellmann M, Boni H. Global perspectives on e-waste. Environ Impact Assess Rev 2005;25:436–58.

Wilmoth RC, Hubbard SJ, Bruckle JO, Martin JF. Production and processing of metals: their disposal and future risks. In: Merian E, editor. Metals and their compounds in the environment. Occurrence, analysis and biological relevance. VCH: Weinheim; 1991. p. 19–65.

Wong CSC, Duzgoren-Aydin NS, Aydin A, Wong MH. Evidence of excessive releases of metals from primitive e-waste processing in Guiyu, China. Environ Pollut 2007;148:62–72.

Wu JP, Luo XJ, Zhang Y, Luo Y, Chen SJ, Mai BX, et al. Bioaccumulation of polybrominated diphenyl ethers (PBDEs) and polychlorinated biphenyls (PCBs) in wild aquatic species from an electronic waste (e-waste) recycling site in South China. Environ Int 2008;34:1109–13.

Xing GH, Chan JKY, Leung AOW, Wu SC, Wong MH. Environmental impact and human exposure to PCBs in Guiyu, an electronic waste recycling site in China. Environ Int 2009;35:76–82.

Yang ZZ, Zhao XR, Zhao Q, Qin ZF, Qin XF, Xu XB, et al. Polybrominated diphenyl ethers in leaves and soil from typical electronic waste polluted area in South China. Bull Environ Contam Toxicol 2008;80:340–4.

Zhang J, Min H. Eco-toxicity and metal contamination of paddy soil in an e-wastes recycling area. J Hazard Mater 2009;165:744–50.

Zhao G, Zhou H, Wang D, Zha J, Xu Y, Rao K, et al. PBBs, PBDEs, and PCBs in foods collected from e-waste disassembly sites and daily intake by local residents. Sci Total Environ 2009;407:2565–75.

Zhao GF, Wang ZJ, Dong MH, Rao KF, Luo JP, Wang DH, et al. PBBs, PBDEs, and PCBs levels in hair of residents around e-waste disassembly sites in Zhejiang Province, China, and their potential sources. Sci Total Environ 2008;397:46–57.

Zhao GF, Xu Y, Han GG, Ling B. Biotransfer of persistent organic pollutants from a large site in China used for the disassembly of electronic and electrical waste. Environ Geochem Health 2006;28:341–51.

Zheng LK, Wu KS, Li Y, Qi ZL, Han D, Zhang B, et al. Blood lead and cadmium levels and relevant factors among children from an e-waste recycling town in China. Environ Res 2008;108:15–20.